TESTING OF NEW FERROELECTRIC ELEMENTS CUSTOM ENGINEERED FOR EXPLOSIVELY DRIVEN FERROELECTRIC APPLICATIONS

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Abstract

Explosively driven ferroelectric generators (FEGs) are reliable, compact, high voltage sources that utilize high pressures to liberate charge trapped in the crystal structure of ferroelectric materials. For the active ferroelectric element most FEG designs use commercial lead zirconate-titanate (PZT) compositions designed for either precision actuators or naval sonar transducers. However, the material properties that are important in FEG applications are not the same material properties for which these materials have been designed to maximize. FEG designs utilizing these commercial materials are performance limited by high voltage breakdown, mechanical failure and low energy densities. TRS Technologies inc. has produced a new series of ferroelectric elements designed specifically for FEG applications. HEM Technologies has performed dielectric strength and shock compression experiments on these new materials to evaluate their performance in comparison to existing commercially available materials.

I. BACKGROUND

Ferroelectrics are a type of piezoelectric material that has a crystalline structure with a permanent electric dipole that can remain stable in two or more orientations. These orientations can be switched through application of high temperatures, high mechanical stresses or high electric fields. For cost and durability reasons most ferroelectric materials are manufactured as polycrystalline ceramics rather than single crystals. Within the polycrystalline ceramic there are domains of like polarization however adjacent domains assume opposite polarization to minimize internal energy. During manufacture energy is stored in the element by aligning the polarization of these domains, a process called poling.

Application of weak external mechanical stresses to a ferroelectric element will result in temporary charge displacement onto the surface of the ferroelectric element. The charge imbalance across the element acts as a charged capacitor, providing energy that can be applied to perform work. When the external stresses are removed, the charge imbalance is corrected and the charges flow back. Operation in this low pressure regime is simply piezoelectric in nature and little or no reorientation of the ferroelectric domains occurs. As the magnitude of the applied mechanical stress is increased, conditions become favorable for the crystal domains to reorient to a new minimum internal energy state. When the domains reorient the charges trapped by their dipole moment are permanently released, this is referred to as depolarization.

A FEG creates usable electrical energy from the chemical energy stores in high explosives (HE) by either utilizing the piezoelectric properties of the ferroelectric material to directly convert the chemical energy or by depolarizing the element and releasing the energy stored in the domain structure during manufacture.

II. MATERIALS

Two different types of ferroelectric elements designed for shock depolarization were tested, TRS Technologies' High Voltage Shock Discharge Elements (Shock-HV) and High Current Shock Discharge Elements (Shock-HC).

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14. ABSTRACT

Explosively driven ferroelectric generators (FEGs) are reliable, compact, high voltage sources that utilize high pressures to liberate charge trapped in the crystal structure of ferroelectric materials. For the active ferroelectric element most FEG designs use commercial lead zirconate-titanate (PZT) compositions designed for either precision actuators or naval sonar transducers. However, the material properties that are important in FEG applications are not the same material properties for which these materials have been designed to maximize. FEG designs utilizing these commercial materials are performance limited by high voltage breakdown, mechanical failure and low energy densities. TRS Technologies inc. has produced a new series of ferroelectric elements designed specifically for FEG applications. HEM Technologies has performed dielectric strength and shock compression experiments on these new materials to evaluate their performance in comparison to existing commercially available materials.

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These materials are specially designed to operate in the ferroelectric depolarization regime unlike other commercial ferroelectrics which are designed to resist depolarization. Two Type I Navy PZT elements; EDO Corporation's EC-64 and TRS Technologies' TRS100 were tested for comparison. Although the materials can be manufactured in a wide array of geometries, the samples tested where all 25.4 mm diameter axially poled right cylinders of varying thickness.

Table 1 lists the material samples tested, providing the dimensions as well as a few selected properties of the material. t is the height of the right cylinder and Ø is the diameter of the cylinder. The piezoelectric charge constant of the material, d_{33}, is a common measure of the piezoelectric sensitivity of the material, providing a linear approximation of the polarization that will be induced in the material by an applied mechanical force. The subscript indicates the direction of polarization and the direction of excitation, with 33 indicating both to be in the axial direction. ε_r is the relative permittivity of the material.

Table 1. List of materials tested.

Material	t (mm)	Ø (mm)	d_{33} (pC/N)	ε_r
TRS Shock-HV Thick	5.08	25.4	75	300
TRS Shock-HV Thin	0.91	25.4	75	300
TRS Shock-HC Thick	2.79	25.4	75	300
TRS Shock-HC Thin	1.60	25.4	75	300
EC-64	5.08	25.4	290	1300
TRS100	5.08	25.4	350	1450

III. EXPERIMENTAL SETUP

Because only a limited number of the experimental materials were available only the two most relevant experiments were performed; a shock depolarization test into a low impedance load, and a dielectric breakdown test. The electric current measurement obtained from the shock depolarization test can be integrated to find the total charge liberated from the sample. The peak charge release can be used to estimate energy and power generated into other loads. Dielectric strength measurements are also an important measure of usefulness. High voltages are easily reached with high impedance loads causing the breakdown strength of the element to become the limiting factor. The combination of these two properties will allow approximation of the device behavior in a number of practical situations.

A. Dielectric Breakdown

The electrode and sample geometry for the dielectric breakdown tests is shown in Fig. 1. As manufactured the ferroelectric samples had thick-film silver electrodes on the top and bottom that covered the full diameter of the sample. However, to ensure bulk breakdown of the sample the electrodes cannot extend to the edges of the cylinder face. For the dielectric breakdown tests, the factory plated electrodes were gently removed using silicon carbide abrasive. The ferroelectric sample was then sandwiched between two brass Bruce-profile electrodes with a base diameter of 25.4 mm and a 10 mm diameter flat. The electrode-sample assembly is then submerged in a transformer oil bath and out-gassed to 100 millitorr to remove trapped air bubbles.

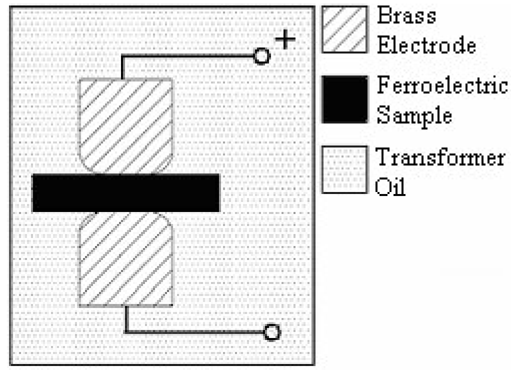

Figure 1. Electrode and sample geometry for the dielectric breakdown testing.

The sample is then connected to a pulsing system that applies a 32 kV pulse with a 10 μs risetime to approximate the voltage stress the material would experience under high mechanical drives [3]. The voltage at which the sample fails approximates the absolute maximum voltage achievable from a FEG design using this material.

B. Shock Depolarization

For the shock compression tests, the elements are sandwiched between two buffers as shown in Fig. 2. The buffers allow the shockwave to slow down, expand and lose energy to minimize shock-induced conductivity; while also functioning to temporally separate the noise created by the exploding bridge-wire detonator (EBW) and the ferroelectric reaction. For the Shock-HV, EC-64 and TRS100 elements, the connections are on upper and lower faces of the element, for these materials the buffers are made out of aluminum, which also serves as the electrical connection. For the Shock-HC elements, the electrical connections are on the sides, so conductive buffers are not acceptable, for these elements alumina bisque is used as the buffer material. The circumferential surface of the ferroelectric sample was covered with an RTV silicone to increase voltage hold-off across the outside of the sample.

The samples were subjected to axial applied high pressures generated by a 6g conical charge of composition C-4 high explosive while connected to a ~1 Ohm load (1.12 Ω, 97 nH). The current was measured using a passive current monitor, and numerically integrated during post-processing to find the liberated charge. These two values approximate the maximum current achievable from a FEG design utilizing this material.

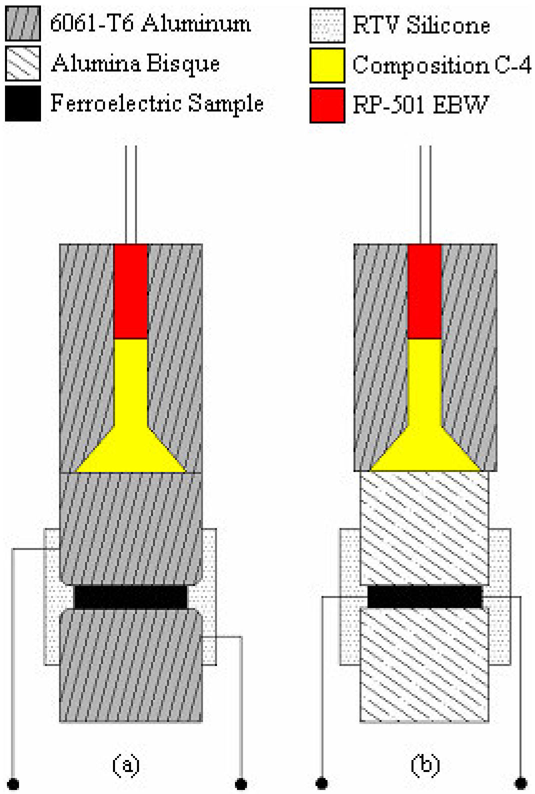

Figure 2. Geometry of the shock depolarization setup for (a) Shock-HV, EC-64 and TRS-100 elements, and (b) Shock-HC elements.

IV. EXPERIMENTAL RESULTS

A. Dielectric Breakdown

The dielectric breakdown tests were performed on the Shock-HV samples and the commercial PZTs. Shock-HC samples were not tested because sufficient samples were not available to do both the breakdown and depolarization tests. Fig. 3 shows the time domain results of the breakdown tests. Both of the waveforms from the Shock-HV samples are included but only a single typical sample of each of the commercial materials is shown. The final dielectric strength of each of the samples is shown in Fig. 4.

There is a disturbance in the rising edge of the applied voltage measurement for the two thick Shock-HV samples. This disturbance is most likely due to a partial breakdown of the ferroelectric sample. The partial breakdowns were physically manifested as discolored dendrite patterns on and just below the surface of the element; these patterns are shown in Fig. 5. This discharge did not immediately cause dielectric failure but may have weakened the element. Interestingly, both the voltage artifact and dendrite patterns occurred on both of the thicker Shock-HV samples but not on any of the other materials. The precise cause of this phenomenon is currently unknown.

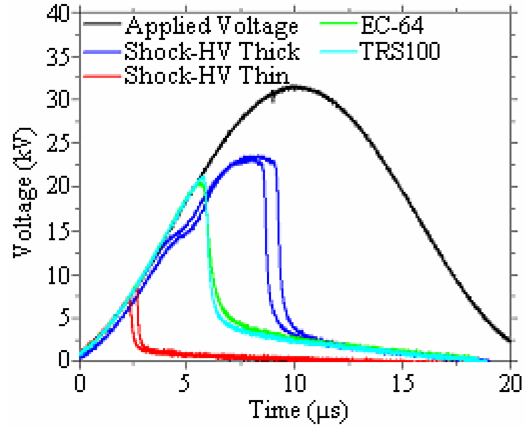

Figure 3. Time domain results of the dielectric breakdown testing.

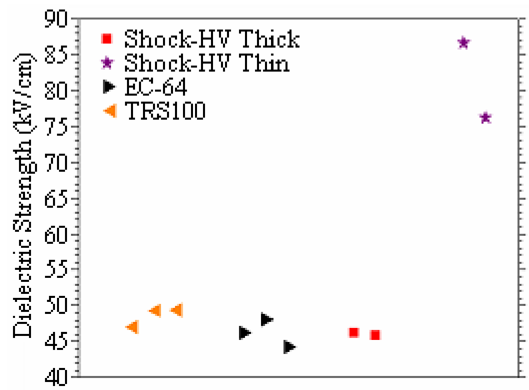

Figure 4. Dielectric strength measurements by material.

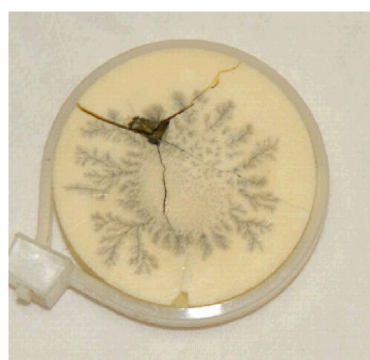

Figure 5. Dendrite patterned discolorations on the thick Shock-HV samples.

B. Shock Depolarization

The data from the best performing sample of each material is shown in Table 2. The capacitance of the element was measured prior to testing using an LCR meter. The current is measured using a passive current monitor and the voltage was measured with a Tektronics

1000x voltage probe. The power is the peak value obtained by multiplying the two waveforms. The energy deposited in the load is calculated by numerical integration of the power. Any energy contributed by the negative relaxation current is excluded from this value. The pulsewidth is measured as full width half maximum of the current and the risetime is the 10%-90% time of the current waveform.

Several selected current waveforms are included below. The current produced by one of the Shock-HC thin samples is shown in Fig. 6. Fig. 7 is the current from a thick Shock-HV sample. The Shock-HV samples have relatively fast risetimes and short pulses while the Shock-HC samples provide notably long pulses.

Table 2. Shock depolarization results.

	Shock-HC Thick	**Shock-HC Thin**	**Shock-HV Thick**	**Shock-HV Thin**	**EC-64**	**TRS100**
Capacitance (nF)	487	250	0.27	1.47	1.15	1.28
Current (A)	151	55.1	327	47	113	117
Voltage (V)	170	60.9	361	52.6	124	131
Power (kW)	25.5	3.36	118	2.47	13.8	15.2
Energy (mJ)	68.9	22.6	35.1	0.32	9.89	16.7
Energy D. (mJ/cm^3)	48.9	27.9	13.7	0.69	3.85	6.50
Charge (µC)	700	458	165	6.1	112	123
Pulsewidth (µs)	3.58	8.88	0.34	0.13	0.95	1.02
Risetime (µs)	1.48	2.10	0.20	0.07	1.13	0.73

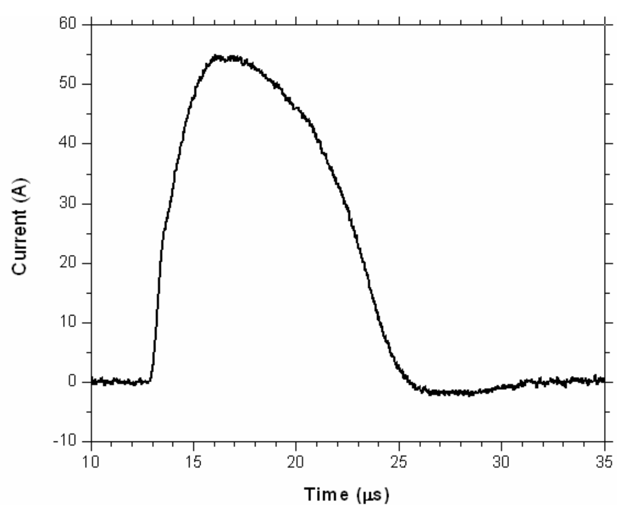

Figure 6. Current from a thin Shock-HC sample.

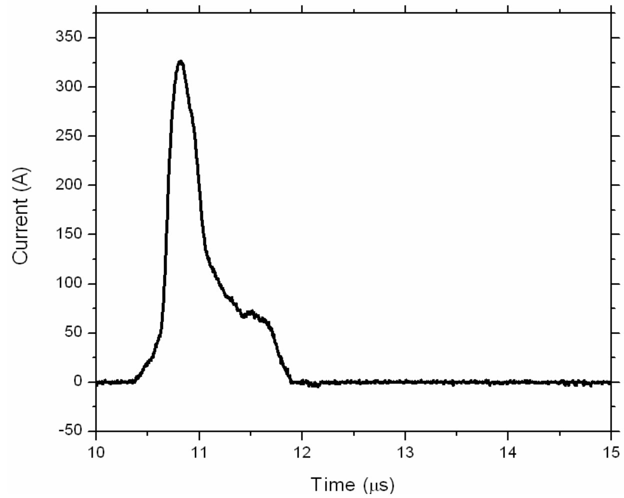

Figure 7. Current from a thick Shock-HV sample.

V. CONCLUSIONS

More testing is required to produce statistically valid conclusions, however based on the small sample population in this study the Shock-HV and Shock-HC samples both appear to outperform the types of materials currently used in FEG designs. The thick Shock-HV samples provided almost an order of magnitude more power without power conditioning systems, making them ideal for direct drive applications.

Future studies will work to increase the sample population to improve the statistical data on the materials. Further shock depolarization testing into varying loads might be performed to identify and quantify loss mechanisms at high drive levels. Measurements of the pressures produced by the explosive charges used in this study would be useful to allow comparison to other material characterization tests. HEM Technologies intends to integrate these materials into its self-contained high voltage / high current FEG systems.

VI. REFERENCES

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